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Pesticide Side-Effects on Arthropod Natural Enemies
A Database Summary

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In addition to characterizing the literature, all pesticide/natural enemy response data were translated to a scale ranging from 1 (0% effect) to 5 (90-100% effect). Lethal and sublethal effects are presented for many species, pesticide and test method data groupings. Some general trends from the database are that predators are less susceptible and more variable in response to pesticides than parasitoids. Some species very tolerant to pesticides are the spider, Lycosa pseudoannulata, the coccinellid, Cryptolaemus montrouzieri, and the chrysopid, Chrysopa carnea. Insecticides are the most toxic pesticide class to predators and parasitoids, followed by herbicides, acaricides and fungicides, respectively. Among insecticide classes, a trend of increasing toxicity to natural enemies is present from the early inorganics to the synthetic pyrethroids. More recent microbials and insect growth regulators seem less toxic and more selective. Differences in the susceptibility trends among pests, predators and parasitoids are discussed.

17. KEY WORDS AND DOCUMENT ANALYSIS

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Pesticide Side-Effects on Arthropod Natural Enemies: a Database Summary

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ABSTRACT

Theiling, K.M. and Croft, B.A., 1988. Pesticide side-effects on arthropod natural enemies: a database summary. *Agric., Ecosystems Environ.*, 21: 191-218.

The literature on pesticide side-effects on arthropod natural enemies has greatly expanded since the 1950s. A database (SELCTV) of this literature has been developed for characterization, analysis and use in decision-making for pest control and environmental impact assessment. Currently, the database holds some 12 600 records containing pesticide side-effects information for over 600 species of natural enemies and 400 agricultural chemicals. Each database record is composed of 40 fields. A record includes information on the natural enemy species tested, the chemical pesticide and its attributes, the conditions of pesticide exposure and associated natural enemy response, and the literature source of the information.

In addition to characterizing the literature, all pesticide/natural enemy response data were translated to a scale ranging from 1 (0% effect) to 5 (90-100% effect). Lethal and sublethal effects are presented for many species, pesticide and test method data groupings. Some general trends from the database are that predators are less susceptible and more variable in response to pesticides than parasitoids. Some species very tolerant to pesticides are the spider, *Lycosa pseudoannulata*, the coccinellid, *Cryptolaemus montrouzieri*, and the chrysopid, *Chrysopa carnea*. Insecticides are the most toxic pesticide class to predators and parasitoids, followed by herbicides, acaricides and fungicides, respectively. Among insecticide classes, a trend of increasing toxicity to natural enemies is present from the early inorganics to the synthetic pyrethroids. More recent microbials and insect growth regulators seem less toxic and more selective. Differences in the susceptibility trends among pests, predators and parasitoids are discussed.

INTRODUCTION

Early reviews of the influence of pesticides on arthropod natural enemies focused primarily on toxicity, selectivity and ecological effects, and were largely comprehensive to all groups of pesticides, predators and parasitoids (Ripper, 1956; Stern et al., 1959; van den Bosch and Stern, 1962; Bartlett, 1964). Similar reviews have become less common (e.g. Kirknel, 1974; Croft and Brown,

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1975), probably as a result of the breadth of research that has evolved over the past few decades in this field.

Recent reviews have emphasized more specialized areas of natural enemy/pesticide research, such as side-effects of a particular pesticide group (e.g. synthetic pyrethroid insecticides (Niemczyk et al., 1981; Croft and Whalon, 1982), microbial pesticides (Flexner et al., 1986), insect hormone analogues (Beckage, 1985). Others have reviewed standardized side-effects testing (Croft, 1977; Hassan et al., 1983), modes of pesticide uptake (Croft, 1977), pesticide selectivity (Gruys, 1980; Hull and Beers, 1985; Mullin and Croft, 1985) resistance development (Croft and Strickler, 1983; Fournier et al., 1986), and genetic improvement and use of pesticide-resistant strains in integrated pest management (IPM) (Croft and Hoyt, 1983; Hoy, 1985).

The literature on natural enemy/pesticide research has grown rapidly since the mid 1970s (Croft and Brown, 1975; Croft, 1977). Methods of evaluation have become more specific and precise (Theiling, 1987). Comprehensive summarization using traditional methods has become limited; however, computer database techniques allow rapid processing of large information sets.

In this review, data published over the past 40 years on pesticide side-effects of arthropod natural enemies of agricultural pests are summarized using a database (SELCTV). Information comes from nearly 1000 research publications, translating into nearly 12 600 database records. Included in the database are the effects of over 400 agricultural chemicals on 609 species of predators and parasitoids. Many specific analyses conducted cannot be cited here because of space limitations (for more detailed analysis and total literature base see Theiling, 1987).

The purpose of summarizing existing work is several-fold: e.g. to provide a tabulation of research, to elucidate trends from a perspective not previously possible, to evaluate hypotheses regarding species susceptibility and pesticide toxicity, to develop selectivity charts by crop and to evaluate test protocols for standardization. Efforts are underway to make SELCTV more widely available to researchers and extension personnel.

DATABASE METHODS

Data were extracted from the literature, primarily from papers published in refereed journals. Minor data sources included research bulletins and dissertations. Studies in which statistical analysis was not performed, or where replication, sample size or controls were deemed inadequate were classified in a database field added for this purpose (DAT:RATING; Table 1). These data can be selectively excluded from analyses. However, results presented here are taken from the entire database. The database represents a population of natural enemy response data to pesticides. Descriptive statistics, means and variance estimates were employed for comparative analyses.

TABLE 1

Field names and descriptions for SELCTV record structure

SELCTV Subdivision: Biological	
GENUS:	taxonomic genus of the tested organism
SPECIES:	taxonomic species of the tested organism
FAMILY:	taxonomic family of the tested organism
NE:ATTRIBU:	coded field of 5 natural enemy attributes (1)ORDER (2)NE:TYPE (3)SEX (4)SOURCE (5)SUSCEPT. STATUS
STAGE:	lifestage of the organism at the time of testing
PROD:UNIT:	crop with which natural enemy is associated
LOCI:	location where the research was conducted
HOST:PREY:	host/prey of the tested natural enemy
HP:TOX:DAT:	host/prey toxicity data in publication? (y/n)
SELCTV Subdivision: Chemical	
CPD:NAME	experimental or common chemical name of toxicant
FORMULATN:	commercial formulation or trade name
CHEM:CLASS:	type of pesticide, e.g. fungicide(f)
CHEM:GROUP:	chemical structure classification, e.g. carbamate or synthetic pyrethroid
CHEM:RATE:	rate or manner of application e.g. dose, residue
CR:UNITS:	units in which application was measured
CR:VALUE:	numeric value associated with rate units
SC:AI:	standard concentration in %ai
SELCTV Subdivision: Test and Summary	
DUR:EXP:	duration of actual contact with the toxicant
TST:METHD:	method used for susceptibility assessment
EVAL:TIME:	time elapsed from initial exposure to evaluation
RESP:TYPE:	response being measured, e.g. LD50, mortality
RESP:UNITS:	response units, e.g. %+, %−, or units of assay
RESP:VALUE:	numerical value associated with RESP:UNITS
RR:RATIO:	resistant strain LD50/susceptible strain LD50
TOX:RATING:	common response rating scale, ranging from 1-5
DAT:RATING:	scale for rating precision level and statistics
SUBLETHAL:	effects of non-lethal doses, e.g. fecundity
SLECTRATIO:	LD50 of host or prey/LD50 of natural enemy
COMMENTS:	any other relevant features of the paper
REFERENCE Subdivision: Bibliographic	
REF:NUM:	unique identifying number assigned to each paper
AUTHOR:	author(s) of paper from which the data is extracted
PUB:DATE:	year of publication
TITLE:	title of the publication
JOURNAL:	scientific or technical journal of publication
VOLUME:	volume and number of journal
PAGES:	page numbers of publication
LANGUAGE:	language in which paper was published
ABSTRACT:	paper, abstract or both?
RECORDS:	number of records extracted from the publication
KEYWORDS:	topics of focus within the publication

Each record in SELCTV represents one screening of a pesticide on one natural enemy species under the cited conditions. A total of 40 fields comprised each record. Table 1 presents the record structure and a brief explanation of content. While some subjectivity was necessary in converting data from literature to record format, care was taken to preserve data integrity while maintaining consistency within the database.

Elements of the literature base are characterized in the order of their appearance in the database record structure (Table 1). Because study of pesticide impact on natural enemies is evolving rapidly, time trends are presented for several factors. Analysis based on toxicity and selectivity follows characterization. General trends from the literature and future research directions are discussed.

RESULTS

Database characterization

Record attributes

A plot of database records over time indicates the growth rate of research (Fig. 1). Record numbers increased after 1945, with a sharp upturn after 1955. This rate of increase has continued to the present. (The negative slope of lines after 1980 is believed to reflect incomplete literature collection, rather than an actual decline in research.)

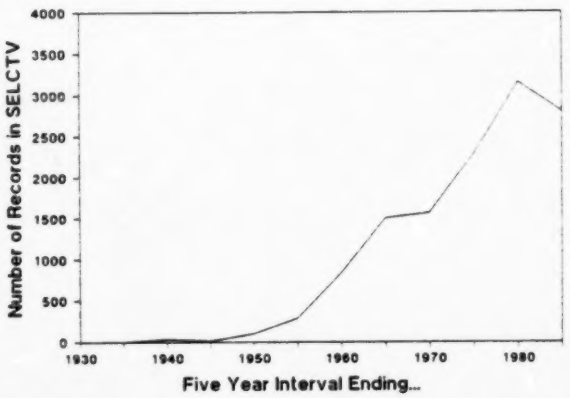

Fig. 1. Incidence over time of records of pesticide impact on arthropod natural enemies from the SELCTV database.

Natural enemy attributes

Predator susceptibility to pesticides accounted for 71% and parasitoids 29% of test records. Thirteen arthropod orders were represented, 10 in the Insecta and 3 in the Arachnida. The most common were: Hymenoptera (27% of records); Coleoptera (22%); predaceous mites (Acari 19.2%); Hemiptera (14.1%); Neuroptera (8.7%); Diptera (4.6%); Araneae (2.5%); Thysanoptera (1.3%); 5 others.

Pesticide side-effects research includes data on 88 families. The 15 most common were Phytoseiidae (17.3% of records), Coccinellidae (17.2%), Braconidae (8.5%), Chrysopidae (8.2%), Miridae (6.0%), Aphelinidae (4.5%), Ichneumonidae (3.8%), Anthocoridae (3.5%), Trichogrammatidae (3.4%) Carabidae (2.9%), Syrphidae (2.8%), Encyrtidae (2.8%), Lygaeidae (1.8%), Nabidae (1.8%) and Eulophidae (1.5%). The Braconidae, Aphelinidae, Ichneumonidae and Trichogrammatidae, respectively, were the most common parasitoid families.

The 15 most prevalent species in the database were: *Chrysopa carnea* (591 records); *Amblyseius fallacis* (574); *Coccinella septempunctata* (440); *Hippodamia convergens* (375); *Phytoseiulus persimilis* (323); *Typhlodromus pyri* (268); *Encarsia formosa* (232); *Typhlodromus occidentalis* (213); *Trichogramma cacoeciae* (158); *Chrysopa oculata* (137); *Stethorus punctum* (134); *Metasyrphus corollae* (134); *Phygadeuon trichops* (124); *Leptomastix dactylopii* (117); *Cryptolaemus montrouzieri* (114); *Coleomegilla maculata* (103). *Encarsia formosa*, sixth ranked by species, was the most common parasitoid. *Encarsia formosa* has been managed in greenhouse IPM programs, and has been thoroughly tested for susceptibility to many pesticides (e.g. Hassan et al., 1983). Only 4 of the above species are parasitoids, all of the Hymenoptera.

A single life stage was tested in over 65% of assays. Adults were most commonly tested, accounting for 46.7% of assays. Immature forms comprised 14.5% of tests, while eggs and pupae accounted for only 2% each. A particular life stage was not specified 32% of the time, usually because of treatment of many stages in field tests.

The literature base contains pesticide impact data for natural enemies from 60 different crops. Primary cropping systems included apple (23% of records), cotton (11%), citrus (9%), alfalfa (5%) and greenhouse production (4%).

Predominant host or prey of natural enemies featured in pesticide-impact research were phytophagous mites (18% of records) and aphids (18%). Homoptera (excluding aphids) including scales, mealybugs, psyllids and whiteflies, comprised another 12%. Most hosts or prey identified were indirect or secondary pests. Generally, biological control agents for these species have been more effective than for primary pests of agriculture (Hoyt and Tanigoshi, 1983).

Chemical attributes

Insecticides comprised 82% of pesticide impact assessments on natural enemies, fungicides 9%, acaricides 7% and herbicides only 1.4%. Side-effects of

feeding repellents, fumigants, nutrient sprays and plant growth regulators comprised less than 0.5% of records. Figure 2 gives the incidence of assessments over time for each of the 4 major pesticide classes. The preponderance of insecticide data is striking. Only in the past decade have impact studies become more inclusive of other pesticides.

Pesticide classes were further partitioned by chemical structure. The 10 most common chemical groupings accounted for nearly 90% of published research: organophosphates (40%); carbamates (13%); organochlorines and DDT derivatives (7% each); synthetic pyrethroids (6%); miscellaneous organics (5%); microbial insecticides (4%); inorganics and botanicals (3% each); juvenile hormone analogues (2%). These groupings primarily contain insecticides. Figure 3 gives the incidence of assessments over time for major insecticide groups.

The compounds most thoroughly documented for their impact on natural enemies were insecticides: carbaryl (494 records); DDT (476), malathion (436); parathion (430); dimethoate (390); azinphosmethyl (373); diazinon (266); permethrin (239); demeton (237); trichlorfon (224); endosulfan (210); oxydemeton-methyl (204); parathion-methyl (203); pirimicarb (200); fenvalerate (184). The most commonly tested acaricides were dicofol (155) and cyhexatin (112), while the most prevalent fungicide was captan (113). Over 50% of susceptibility assessments were made using organophosphate insecticides.

Slightly more than half of the susceptibility assessments specified the formulation or trade name of the pesticide being tested. Emulsifiable concentrate (37% of records) and wettable powder (29%) were the most widely reported formulations. Others included granular (5%), solubles (3%), flowables (2%)

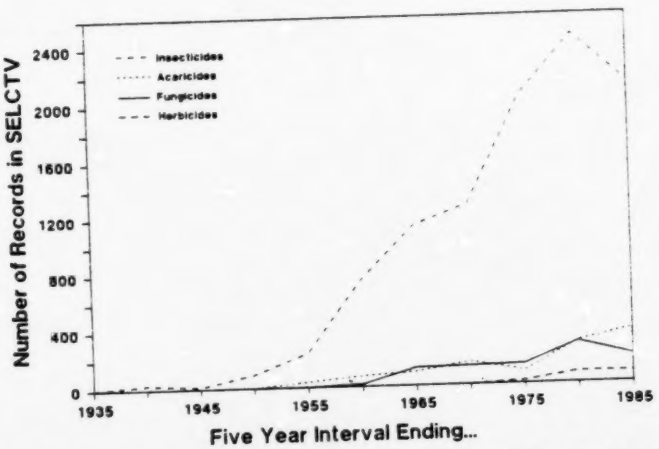

Fig. 2. Incidence over time of pesticide impact research on arthropod natural enemies for each major pesticide class from the SELCTV database.

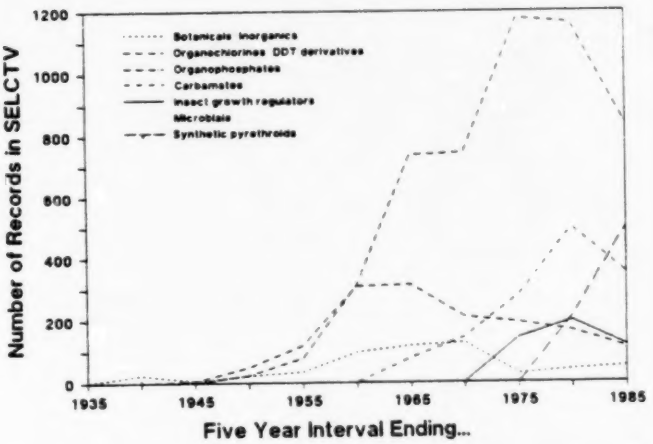

Fig. 3. Incidence over time of insecticide impact research on arthropod natural enemies for major insecticide classes from the SELCTV database.

and dusts (1%). Approximately 10% of records documented the effects of technical-grade pesticides on natural enemies.

Test and summary attributes

Ten different test methods were differentiated from the literature documenting pesticide impact on natural enemies (Fig. 4). Field and (fresh residue) contact tests each accounted for about 30% of assays. Tests in which pesticides were sprayed, applied topically, contacted as aged residues or used as dips were conducted 6–7% of the time. Pesticides were administered orally, by injection or where the mode of uptake was variable in another 5% of tests. Assays in which the host of an endoparasitoid was treated with a microbial insecticide comprised less than 1% of tests.

Trends in test methodology over time (Fig. 5) indicate that laboratory contact tests have surpassed field tests in frequency. Topical, residue and dip tests show similar trends of rapid increase from 1965 to 1975, reaching a plateau by the late 1970s at about 30% of the level of contact or field tests. Tests in which the toxicant is sprayed on the natural enemy have maintained a fairly steady rate over the last 15 years, slightly below that of the other 5 methods. Residue and contact tests have been cited as those which best simulate field exposure (Croft, 1977; Hassan et al., 1983).

The relative precision associated with side-effects testing was evaluated by comparing the frequency of field tests versus LC_{50} or LD_{50} assays over time (Fig. 6). Field tests dominated early impact assessments, increasing abruptly from 1955 and peaking by 1970. Median lethal assays began a more gradual

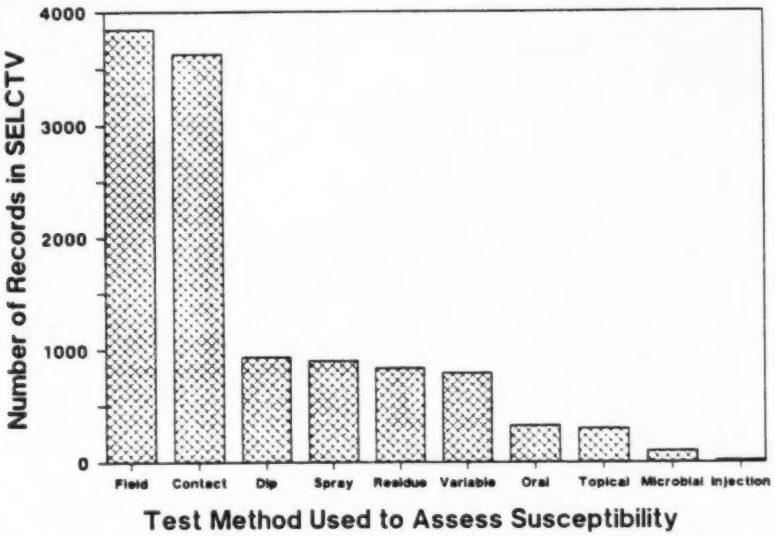

Fig. 4. Distribution of SELCTV database records of pesticide impact on arthropod natural enemies grouped by test method.

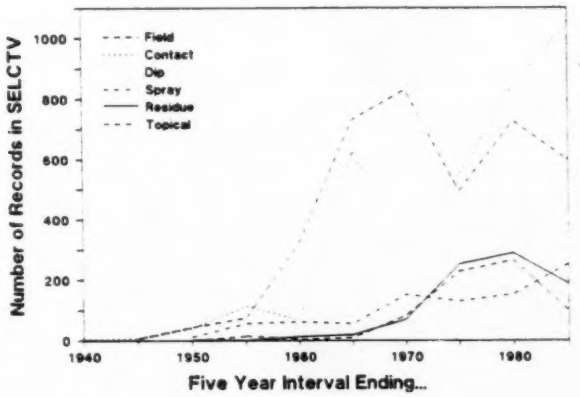

Fig. 5. Incidence of predominant test methods used to assess natural enemy susceptibility to pesticides in number of records over time from the SELCTV database.

increase around 1955, increasing sharply after 1970. Field assessments have slowly decreased relative to total records.

The rate of pesticide applied in 70% of tests was the recommended field rate or other concentrations appropriate for pest control. Results of LC_{50} and LD_{50} assays are not direct indicators of pesticide impact at field rates. Natural ene-

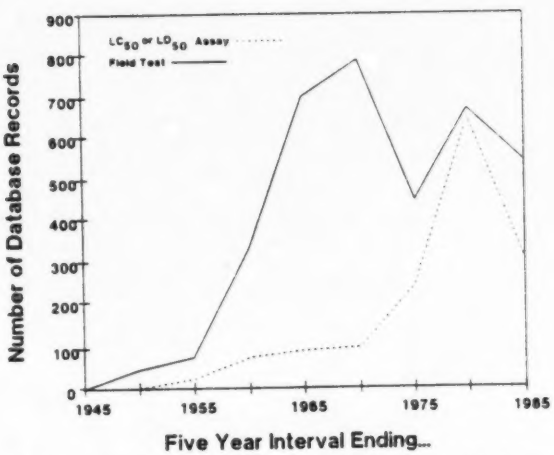

Fig. 6. Changes in precision associated with pesticide impact assessment on arthropod natural enemies measured in records of field versus median lethal assays over time from the SELCTV database.

mies were exposed to pesticides applied at a given concentration in 22% of tests, to a specified dose in 2% of tests and to a residual deposit in 6%.

The time that a natural enemy was in contact with the toxicant during testing ranged from ≤ 24 h to ≥ 1 month as reported in the literature. Exposure times of ≤ 24 h were most common, and were used in 18% of tests. Declining numbers of tests were conducted at longer exposure intervals. A similar pattern was seen with evaluation time, the elapsed time from initial pesticide exposure to evaluation of impact. Most tests of pesticide side-effects on natural enemies have been evaluated in ≤ 48 h, with fewer records in categories > 48 h.

Response type, the measured side-effect of a pesticide on a natural enemy, varied among 27 responses reported in the literature. Mortality from field rate (or related concentrations) was measured in over 75% of the time. Median lethal dose (LD), concentration (LC) or time (LT) were measured in another 20% of assays. Remaining measurements were of sublethal responses such as changes in predation, ability to diapause, fecundity, oviposition and developmental time.

A toxicity rating was employed as a means to compare any data subset on a common scale of units. While toxicity ratings encompassed all response types (e.g. mortality, decreased fertility or fecundity), nearly 95% of assessments were based on mortality, including median lethal assays. Toxicity ratings indicate the severity of a pesticide-induced effect. Ratings included: 1 (0% effect); 2 ($< 10\%$); 3 (10–30%); 4 (30–90%); 5 ($> 90\%$). Most analyses were based on mean toxicity ratings computed for database records grouped by nat-

ural enemy, pesticide or test attributes or combinations of attributes (see Table 1).

Sublethal effects of pesticides were reported in 8% of tests. Fecundity was most commonly observed, accounting for 30% of sublethal reports. Changes in predation, parasitism, developmental time, fertility, longevity and morphology each accounted for c. 10% of reported sublethal side-effects. The frequency of sublethal response measurements in side-effect testing was evaluated over time. Following a slow increase since 1960, relative to total records, nearly 13% of current studies report sublethal effects. Many recent studies have carefully examined pesticide-induced sublethal responses among natural enemies (e.g. Lawrence, 1981; Grapel, 1982; Perera, 1982; Moosbeckhofer, 1983; Hoy and Dahlsten, 1984; Grafton-Cardwell and Hoy, 1985; O'Brien et al., 1985).

Selectivity ratios, calculated by dividing the LD_{50} or LC_{50} of the host or prey by that of the natural enemy, were infrequently available in the literature (870 records). Ratios in SELCTV ranged from 0.0001 to >3000, where values <0 indicated selectivity to natural enemies. Nearly 80% of selectivity ratios were reported for predators and their prey, while 20% compared the impact of pesticides on parasitoids and their hosts. Selectivity ratios were most commonly reported for natural enemies within the Coleoptera (29%), Acari (20%), Hymenoptera (20%) and Araneae (11%).

Analysis of the database

Toxicity: by natural enemy attributes

Table 2 shows the combined responses of predators and parasitoids to the major pesticide classes from database records. Overall, predators were less susceptible (i.e. had a lower average toxicity rating) than parasitoids. Greater susceptibility was exhibited by parasitoids compared with predators for each pesticide class with the exception of fungicides, for which responses were similar. In most cases, parasitoids exhibited a less variable response to pesticides than predators. Insecticides were most toxic to both groups of natural enemies, followed by herbicides, acaricides and fungicides, respectively.

Average toxicity ratings were computed for the 15 most common families using the 1–5 scale: Miridae (3.2); Ichneumonidae (3.2); Chrysopidae (3.2); Lygaeidae (3.3); Anthocoridae (3.3); Nabidae (3.5); Carabidae (3.5); Coccinellidae (3.5); Phytoseiidae (3.5); Aphelinidae (3.5); Trichogrammatidae (3.7); Encyrtidae (3.7); Braconidae (3.7); Eulophidae (3.9); Syrphidae (3.9). Many of the less susceptible families contained predatory natural enemies. Chrysopids and the hemipteran Miridae, Lygaeidae and Anthocoridae were particularly tolerant. Syrphids, important aphid predators, appear to be exceptionally susceptible (e.g. Niemczyk et al., 1981; Hassan et al., 1983; Horn, 1983; David and Horsburgh, 1985).

The apparent tolerance of ichneumonid parasitoids was unexpected. More

TABLE 2

Average toxicity ratings and variances of pesticide classes to all arthropod natural enemies, predators and parasitoids from the SELCTV database

Pesticide class	Predators[1]		Parasitoids		All	
	Mean	Variance	Mean	Variance	Mean	Variance
Insecticide	3.61 (7326)[2]	1.78	3.74 (2989)	1.74	3.65 (10315)	1.77
Fungicide	2.59 (781)	1.51	2.58 (357)	1.45	2.59 (1138)	1.49
Acaricide	2.76 (747)	1.81	2.83 (144)	1.50	2.77 (891)	1.76
Herbicide	2.83 (92)	1.73	3.10 (84)	1.77	2.95 (176)	1.76
All pesticides	3.43 (8968)	1.92	3.57 (3583)	1.86	3.47 (12551)	—

[1]Calculations were made on records of predators, parasitoids and all natural enemies, using the TOX:RATING field in the SELCTV database (1 = 0% mortality; 2 = < 10% mortality; 3 = 10-30% mortality; 4 = 30-90% mortality; 5 = 90-100% mortality).
[2]Number of database records used in calculation.

detailed examination of database records indicated that this may reflect the types of pesticides which have been tested on organisms from this family, rather than their intrinsic susceptibility to all pesticides. A disproportionate amount of ichneumonid tests come from side-effects evaluations of insect growth regulators, fungicides and microbial pesticides (e.g. see large summaries for tests of ichneumonid species in Hassan et al., 1983). Microbial pesticides have been shown to be largely selective to natural enemies (Flexner et al., 1986). We believe these factors contributed to a misleading indication of tolerance in the Ichneumonidae. Furthermore, there are a number of studies in SELCTV documenting the highly toxic effects of conventional pesticides on this family of parasitoids (e.g. Hassan et al., 1983). Selectivity ratio analysis supports the case for high susceptibility for the Ichneumonidae (see later discussion).

Scatterplots and linear regression show the relationship between mean insecticide toxicity and variation in response for the major families of predators and parasitoids (Figs. 7, 8). Parasitoid families showed less variable responses than predators. A negative linear relationship indicated decreasing response variation with increasing susceptibility. Three outliers reduced the slope for predators; otherwise, both regression lines had similar slopes.

Table 3 lists the 15 species most commonly documented in pesticide impact research and their increasing susceptibility to pesticides. Nine of 12 of the most pesticide-tolerant species were predators. Of the phytophagous mite predators (e.g. *P. persimilis*, *T. pyri*, *T. occidentalis*, *A. fallacis* or *S. punctum*), most were

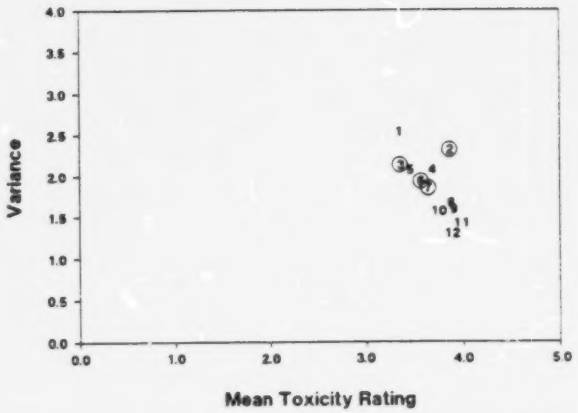

Fig. 7. Mean insecticide toxicity ratings versus variance for 12 families of parasitoids in the SELCTV database. Key to families: 1 = Tachinidae (89 records); 2 = Chalcididae (30); 3 = Scelionidae (42); 4 = Trichogrammatidae (326); 5 = Ichneumonidae (365); 6 = Eupelmidae (27); 7 = Platygasteridae (25); 8 = Pteromalidae (66); 9 = Aphelinidae (382); 10 = Braconidae (1016); 11 = Encyrtidae (280); 12 = Eulophidae (181). Circled values on figure represent families with fewer than 50 database records. Calculations were made on all insecticide records associated with each parasitoid family, using the TOX:RATING field in the SELCTV database (1 = 0% mortality; 2 = < 10% mortality; 3 = 10-30% mortality; 4 = 30-90% mortality; 5 = 90-100% mortality. Regression parameters: $y = -1.2x + 6.3$; $r = -0.72$; mean $x = 3.74$.

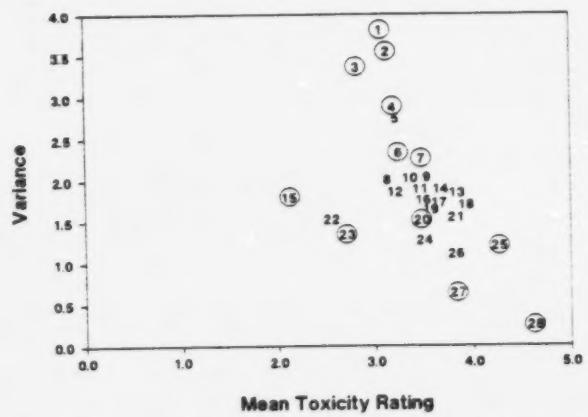

Fig. 8. Mean insecticide toxicity ratings versus variance for 28 families of predators in the SELCTV database. Key to families: 1 = Clubionidae; 2 = Dytiscidae; 3 = Hydrophilidae; 4 = Pentatomidae; 5 = Anystidae; 6 = Reduviidae; 7 = Berytidae; 8 = Lycosidae; 9 = Miridae; 10 = Chrysopidae; 11 = Carabidae; 12 = Malachiidae; 13 = Phloeothripidae; 14 = Hemerobiidae; 15 = Veliidae; 16 = Anthocoridae; 17 = Coccinellidae; 18 = Syrphidae; 19 = Nabidae; 20 = Thripidae; 21 = Phytoseiidae; 22 = Stigmaeidae; 23 = Micryphantidae; 24 = Lygaeidae; 25 = Macrochelidae; 26 = Cecidomyiidae; 27 = Salticidae; 28 = Theridiidae. Circled values on figure represent families with fewer than 50 database records. Calculations were made on all insecticide records associated with each predator family, using the TOX:RATING field in the SELCTV database (1 = 0% mortality; 2 = < 10% mortality; 3 = 10-30% mortality; 4 = 30-90% mortality; 5 = 90-100% mortality). Regression parameters: $y = -0.8x + 4.6$; $r = -0.79$; mean $x = 3.61$.

TABLE 3

Average susceptibility of the 22 most commonly tested natural enemy species to all pesticides from the SELCTV database

Species	Family	No. of Records	Mean Toxicity[a]
Lycosa pseudoannulata	Lycosidae	85	3.0
Cryptolaemus montrouzieri	Coccinellidae	114	3.0
Chrysopa carnea	Chrysopidae	534	3.1
Hyaliodes harti	Miridae	103	3.2
Encarsia formosa	Aphelinidae	232	3.3
Phytoseiulus persimilis	Phytoseiidae	323	3.4
Typhlodromus pyri	Phytoseiidae	268	3.4
Stethorus punctum	Coccinellidae	150	3.5
Typhlodromus occidentalis	Phytoseiidae	205	3.5
Phygadeuon trichops	Ichneumonidae	124	3.5
Chrysopa oculata	Chrysopidae	137	3.5
Amblysieus fallacis	Phytoseiidae	574	3.5
Leptomastix dactylopii	Encyrtidae	139	3.5
Hippodamia convergens	Coccinellidae	375	3.5
Anthocoris nemorum	Anthocoridae	85	3.6
Coccinella septempunctata	Coccinellidae	440	3.6
Trichogramma evanescens	Trichogrammatidae	86	3.6
Trichogramma cacoeciae	Trichogrammatidae	158	3.6
Coleomegilla maculata	Coccinellidae	102	3.7
Amblyseius hibisci	Phytoseiidae	90	3.7
Metasyrphus corollae	Syrphidae	105	4.1
Opius concolor	Braconidae	85	4.3

[a]Calculations were made on records grouped by species across all pesticides, using the TOX:RATING field in the SELCTV database (1 = 0% mortality; 2 = < 10% mortality; 3 = 10-30% mortality; 4 = 30-90% mortality; 5 = 90-100% mortality).

of intermediate susceptibility. Lower average toxicity of pesticides to several predatory mite species was caused by testing pesticide-resistant strains (Croft and Strickler, 1983; Hoy, 1985; Fournier et al., 1986). Individual parasitoid species were well dispersed among natural enemies in terms of susceptibility, with notable tolerance exhibited by *E. formosa*. The high susceptibility of syrphids was again exemplified by *Metasyrphus corollae* (e.g. Grapel, 1982; Hellpap, 1982; Nasseh, 1982).

Life stages of natural enemies differed in their susceptibility to pesticides. Average susceptibilities to all compounds in the database were: eggs (3.0); larvae (3.5); pupae (3.2); adults (3.6). Hence, the more protected egg and pupal stages best tolerated pesticides. The same trend applied to predator lifestages which had identical averages except for adults (3.5). However, egg (3.8) and adult (3.7) parasitoid life stages were the most susceptible, while larvae (3.2) and pupae (3.3) were more tolerant. These trends in susceptibility have been

noted by several reviewers (Croft and Brown, 1975; Croft, 1977; Hull and Beers, 1985) and confirmed in many studies of individual species responses (e.g. Babrikova, 1980, 1982; Warner and Croft, 1982).

Toxicity: by test and pesticide attributes

Mean toxicity ratings were compared by test method across all compounds and natural enemies (see Theiling, 1987 for detailed results). Of the most common tests, field assessments averaged < 3.4; contact, dip and topical tests ranged from 3.5 to 3.6. This small difference does not strongly support the general findings that pesticides may be less harmful under field conditions where refugia, immigration and emigration moderate pesticide impact on natural enemy populations (Croft and Brown, 1975).

Average toxicity values were computed for many pesticide groupings in SELCTV (Table 2; Theiling, 1987). More specifically, insecticide groupings varied widely in their toxicity to natural enemy species (Fig. 9). The distribution of toxicity ratings (1–5) within each insecticide group is presented within a stacked bar histogram. The solid area of each bar represents < 10% mortality, providing an index of harmlessness for each of the major chemical groups arranged chronologically by development. Inorganic and botanical insecticides

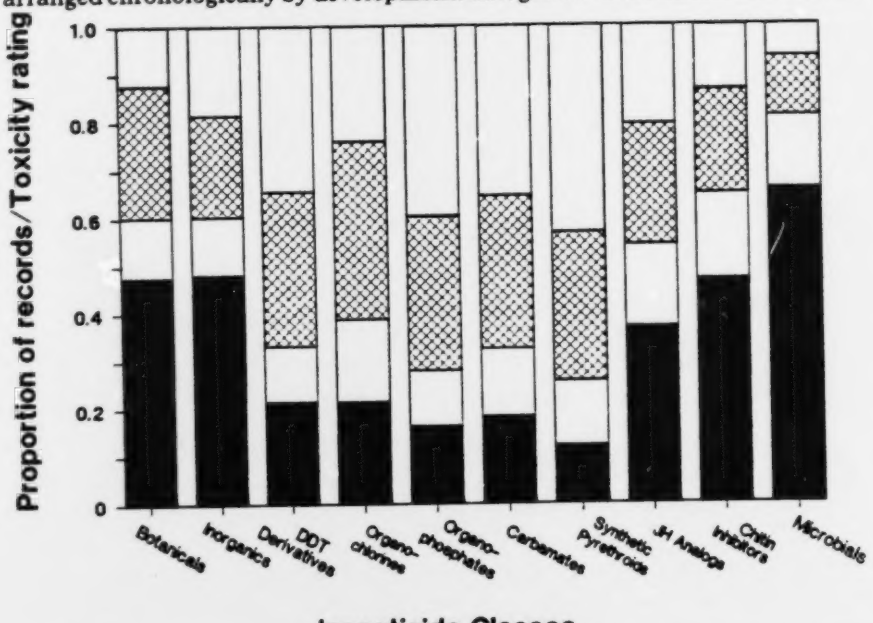

Fig. 9. Distribution of toxicity ratings among insecticide chemical groups assessed for side-effects on arthropod natural enemies from the SELCTV database. ■ = < 10% mortality; □ = 10–30% mortality; ▩ = 30–90% mortality; ◘ = > 90% mortality.

were moderately toxic to natural enemies. Increasing toxicity to non-target arthropods has prevailed since the development of DDT, and has persisted through the synthetic pyrethroids. Chitin-inhibiting growth regulators (benzoylphenyl ureas) and microbial insecticides are more selective to natural enemies than past insecticides.

Three response classes were imposed (based on average toxicity ratings) to rank pesticides: selective (<2.8); moderately toxic (2.8–3.5); harmful (>3.5). Pesticide toxicity was examined at finer levels of resolution using this system (Theiling, 1987). For example, partitioning of microbial insecticides showed microbial by-products (e.g. abamectin) (3.6) and nematode preparations (3.2) could be harmful to natural enemies. The remaining true microbials (protozoa (2.4); viruses (2.2); bacteria (2.1); fungi (1.5)) were relatively innocuous to natural enemy species. Their side-effects are often latent, sublethal or indirect compared with direct, acute toxicity associated with synthetic organic pesticides (Flexner et al., 1986).

Average toxicity was computed for test results of each compound recorded in the literature across all natural enemies, and additionally for predators versus parasitoids where sufficient data were available. Response classes used were as previously described. Of the most commonly tested insecticides (Table 4), DDT, carbaryl, methomyl, azinphosmethyl, malathion, fenvalerate, cypermethrin and permethrin were harmful on the average. Moderate toxicity was noted for the fungicide benomyl, acaricides cyhexatin and dicofol, and insecticides lead arsenate, endosulfan, pirimicarb, phosalone, trichlorfon, hydroprene and chlordimeform. Selectivity to some natural enemies was demonstrated for the fungicides captan and bordeaux mixture, the acaricide tetradifon, and insecticides diflubenzuron and *Bacillus thuringiensis* (B.t.). Hence, the most commonly used pesticides tend to be moderately to highly toxic to natural enemies, while selective compounds are less commonly used and tested. Most compounds were either equally or more toxic to parasitoids than to predators. Broadly divergent effects on natural enemy types were also noted for lead arsenate, endosulfan, carbaryl, phosalone, azinphosmethyl, hydroprene, chlordimeform and permethrin, which were much more harmful to parasitoids than to predators, on the average.

The most hazardous pesticides were also ascertained using average toxicity ratings. Included were the organophosphate insecticides terbufos (4.8), formothion (4.7), pirimiphos-methyl (4.6), EPN (4.4), profenofos (4.4), methamidophos (4.4), parathion (4.3), mevinphos (4.3) and malathion (4.2); the carbamate insecticides methomyl (4.3) and aldoxycarb (4.2); botanical pyrethrins (4.3); deltamethrin (4.4), a synthetic pyrethroid; the acaricides chloropropylate (4.2) and formetanate (4.5); pyrazophos (4.2), a fungicide and paraquat (4.3), a herbicide. These pesticides demonstrated the highest intrinsic toxicity to arthropod natural enemies.

Insecticides with the lowest average toxicity ratings were also identified

TABLE 4

Frequency and average toxicity ratings of common pesticides tested for side-effects on arthropod predators and parasitoids from the SELCTV database

Compound name	All predators[1]			All parasitoids	
	No. of records	Mean toxicity		No. of records	Mean toxicity
Captan	91	1.98		22	2.05
Bordeaux mixture	30	2.03	+[2]	10	1.90
Benomyl	60	3.02	+	20	2.70
Lead arsenate	70	2.40		16	3.25
Endosulfan	143	3.37		66	3.82
DDT	342	3.66		130	3.92
Pirimicarb	166	2.98		34	3.03
Carbaryl	324	3.83		165	4.16
Methomyl	122	4.28		53	4.36
Phosalone	94	3.32		31	3.94
Trichlorfon	136	3.42		88	3.47
Azinphosmethyl	296	3.58		69	3.96
Malathion	311	4.23	+	124	4.10
B.t.	100	2.06	+	103	2.04
Hydroprene	17	2.65		31	3.03
Diflubenzuron	75	2.79	+	68	2.74
Chlordimeform	55	3.02		20	3.35
Fenvalerate	155	3.86	+	29	3.79
Permethrin	178	4.03		58	4.38
Cypermethrin	54	4.24	+	19	3.63
Tetradifon	69	2.13		13	2.54
Cyhexatin	96	2.79		16	3.19
Dicofol	126	2.90		29	2.97

[1]Calculations were made on records grouped by compound name for predators and for parasitoids, using the TOX:RATING field in the SELCTV database (1 = 0% mortality; 2 = < 10% mortality; 3 = 10-30% mortality; 4 = 30-90% mortality; 5 = 90-100% mortality).

[2]The compounds marked + were more toxic to predators than to parasitoids on the average.

(Table 5). Two microbial preparations were very selective. The remaining insecticides covered a greater range of toxicity, exhibiting properties of both ecological and physiological selectivity (Hull and Beers, 1985; Mullin and Croft, 1985). For example, whereas aldicarb and demeton-methyl are primarily systemics and confer ecological selectivity, compounds like B.t. and diflubenzuron may act more on a physiologically selective basis. With the exception of *Beauvaria bassiana* and chlordimeform, all selective compounds identified were more toxic to parasitoids than predators, some (e.g. schradan, ryania, nicotine sulfate, lead arsenate, tepp and perthane) to a large degree.

Acaricides possessing low average toxicity to natural enemies included

TABLE 5

Frequency and average toxicity ratings for the least toxic insecticides to arthropod natural enemies in the SELCTV database

Compound name	Chemical group[1]	Mean toxicity[2]		
		All	Predators	Parasitoids
Beauveria bassiana	m	1.52 (21)[3]	1.72 (11)	1.30 (10)
B.t.	m	2.05 (203)	2.06 (100)	2.04 (103)
Schradan	op	2.23 (35)	2.10 (30)	3.00 (5)
Ryania	bt	2.28 (80)	2.24 (66)	3.50 (14)
Tralomethrin	sp	2.33 (3)	—	—
Chlorfenvinphos	op	2.42 (38)	2.31 (26)	2.67 (12)
Nicotine sulfate	bt	2.45 (80)	2.30 (63)	3.00 (17)
Lead arsenate	io	2.56 (86)	2.40 (70)	3.25 (16)
Fluvalinate	sp	2.60 (5)	2.25 (4)	—
Diflubenzuron	igr	2.76 (143)	2.79 (75)	2.74 (68)
Menazon	op	2.88 (51)	2.77 (48)	4.67 (3)
Hydroprene	igr	2.90 (48)	2.65 (17)	3.03 (31)
Pirimicarb	ca	2.99 (200)	2.98 (166)	3.03 (34)
Vamidothion	op	3.19 (32)	3.16 (25)	3.29 (7)
Aldicarb	ca	3.28 (65)	3.23 (59)	3.67 (6)
Tepp	op	3.30 (33)	3.00 (21)	3.83 (12)
Disulfoton	op	3.31 (48)	3.25 (38)	3.60 (10)
Perthane	dd	3.39 (44)	3.31 (39)	4.00 (5)
Chlordimeform	o	3.43 (108)	3.45 (88)	3.35 (20)
Trichlorfon	op	3.44 (224)	3.42 (136)	3.47 (88)

[1]m = Microbial; op = organophosphate; bt = botanical; sp = synthetic pyrethroid; io = inorganic; igr = insect growth regulator; ca = carbamate; dd = ddt derivative; o = miscellaneous.
[2]Calculations were made on records grouped by compound name for predators, parasitoids and all natural enemies using the TOX:RATING field in the SELCTV database (1 = 0% mortality; 2 = < 10% mortality; 3 = 10-30% mortality; 4 = 30-90% mortality; 5 = 90-100% mortality).
[3]Number of records making up each average.

chlorfenson (2.0), fenbutatin oxide (2.1), tetradifon (2.2), bromopropylate (2.3), benzomate (2.3), chlorobenzilate (2.4), propargite (2.6) and cyhexatin (2.8). With the exception of fenbutatin oxide and chlorobenzilate, predators were less susceptible to these compounds than parasitoids. Tetradifon and cyhexatin were much more toxic to parasitoids than predators.

Certain fungicides were notably low in toxicity: captan (2.0); bordeaux mixture (2.0); captafol (2.0); bupirimiate (2.1); dodine (2.1); vinclozolin (2.1); glyodin (2.2); triadimefon (2.2); zineb (2.3); ferbam (2.3). Captafol and bupirimate were substantially more harmful to predators than to parasitoids. Other fungicides were equally or less toxic to predators than to parasitoids.

Analysis of selectivity ratios

Selectivity ratios were transformed to a log scale (sr:index) to lessen the impact of outliers on averages. The scale ranged from 1 to 9, where a selectivity ratio of 0 (no selective advantage to pests or natural enemies) was equal to an sr:index value of 5. It was believed that selectivity estimates from the literature gave a somewhat distorted perspective of pest/natural enemy comparative susceptibility. The mean of all sr:index values was 4.6, implying that pesticides are slightly less harmful to natural enemies than to pests on the average. There is a tendency for published selectivity data to be partial to compounds showing favorable discrimination for natural enemies over their hosts or prey (499 of 870 cases). Lack of selectivity is less frequently documented because it is the norm.

Predators were favored slightly over their prey by a pesticide application (mean sr:index = 4.5), but hosts were favored over parasitoids (5.2). Mean sr:index values for 12 families of natural enemies separated into 4 approximate classes (Table 6). Carabids had about a 20-fold selectivity advantage over their prey. The next 5 families were 5- to 10-fold more tolerant of pesticides than their prey based on the data reported. Susceptibility of the Braconidae, Miridae, Lygaeidae, Aphelinidae and Phytoseiidae was nearly equivalent to that of their hosts or prey. Finally, the Ichneumonidae were about 20 times more adversely affected by pesticides than were their hosts. While in apparent conflict with previously-mentioned tolerance, closer examination of these records in-

TABLE 6

Average log-transformed selectivity ratios (sr:index) for arthropod natural enemies grouped by family and their associated hosts or prey from comparative pesticide susceptibility tests in the SELCTV database

Family	No. records	Mean SR:index
Carabidae	10	3.70*
Micryphantidae	19	4.16
Nabidae	23	4.22
Coccinellidae	239	4.27
Chrysopidae	72	4.32
Lycosidae	53	4.36
Braconidae	74	4.80
Miridae	11	4.82
Lygaeidae	12	4.83
Aphelinidae	26	4.96
Phytoseiidae	134	5.00
Ichneumonidae	33	6.21

*Calculated from the log-transformed values (sr:index) of the SLECTRATIO (selectivity ratio) field for records grouped by family in the SELCTV database (1-9 scale, 5 = equal impact on natural enemies and pests).

dicates that most of these are comparative tests for ichneumonids and have been run for organosynthetic insecticides rather than for more selective growth regulators or microbial pesticides.

Selectivity data are primarily available for insecticides. The average sr:index value for acaricides (3.7), computed mainly from phytoseiid mite records, demonstrates the selectivity of these compounds to predatory mites over phytophagous mites. By individual compound, the aphicide, pirimicarb (2.8) was the most selective material reported, favoring the natural enemy by more than 150:1 over the host or prey (Table 7). The acaricides cyhexatin and dicofol showed about 20-fold selectivity to natural enemies. Averages for most compounds cluster about the median, neutral value of 5.0. Few sr:index means indicated a pest favored over its natural enemy. Again, this is somewhat of an

TABLE 7

Average log-transformed selectivity ratios (sr:index) grouped by compound for arthropod natural enemies and their associated hosts or prey from comparative susceptibility tests in the SELCTV database

Compound name	No. records	Mean SR:index
Pirimicarb	26	2.77*
Dicofol	11	3.64
Cyhexatin	8	3.88
Thiometon	20	4.30
Demeton	27	4.33
Chlorpyrifos	13	4.38
Aldicarb	11	4.55
Dimethoate	20	4.60
Diazinon	23	4.65
Trichlorfon	9	4.67
Permethrin	44	4.75
Fenvalerate	27	4.78
Parathion	27	4.78
Azinphosmethyl	13	4.80
Carbaryl	25	4.80
Carbofuran	17	4.82
Malathion	37	4.84
Methomyl	17	4.94
Acephate	13	5.00
DDT	17	5.06
Methyl parathion	26	5.12
Lindane	14	5.14
Cypermethrin	22	5.22
Fenitrothion	17	5.47

*Calculated from the log-transformed values (sr:index) of the SLECTRATIO (selectivity ratio) field for records grouped by compound in the SELCTV database (1-9 scale, 5 = equal impact on natural enemies and pests).

anomaly, since the latter compounds are among the most toxic to natural enemy species as indicated by toxicity ratings. Selectivity would be much more in favor of the pest than indicated by the limited selectivity ratios published for them.

CONCLUSIONS FROM DATABASE ANALYSIS

The literature documenting pesticide side-effects on arthropod natural enemies has grown rapidly over the past 30 years, and the present analysis gives no indication that this trend has changed. However, documentation for particular natural enemies, chemicals and methods of assessment has changed over time, in response to changes in pesticide use and integrated pest management (IPM) research (for example, numbers of field tests versus median lethal assays or organochlorine insecticide testing versus synthetic pyrethroids).

An evaluation of publication output shows that the literature has at least doubled in the past decade (1975–1985). Over half of the database source literature was published after 1975. If the literature continues to expand at this rate, it may double again by 1990. These trends document the continued interest in IPM and in the overall side-effects of pesticides, in general.

SELCTV is a relatively comprehensive compilation of pesticide/natural enemy literature (this conclusion is based on literature searches and inspection of references cited in new literature). Updates of accumulating literature are planned for the future. Limitations in the scope of literature currently exist. North American, western European, Australian and middle eastern sources are most complete, while eastern European, Russian and far eastern literature is least well represented. For some foreign journals, only abstracts or English summaries could be obtained.

SELCTV contains only the available published literature. Substantial unpublished data exist on the impact of pesticides on natural enemies. They represent a possible data source for future expansion of SELCTV. In doing so, these data would be identified as unpublished results.

Limitations of database analysis

Drawing conclusions from database summaries should be done with caution, because the distribution of information types and sources is unknown. Literature sampling is not a random process. Furthermore, aggregation of information can obscure subtle influences affecting trends. The discrepancy between toxicity ratings and selectivity data for the Ichneumonidae discussed above was a good example of the need for this caution in interpretation of trends. Specific inspection of the records indicated a bias in information type.

In more global analyses, responses of different strains or biotypes of species, effects of different pesticides, formulations, or doses and different evaluation

methods become merged into aggregate assessments. At best, results can be interpreted as trends which require additional experimental verification. More specific analyses can be conducted to describe susceptibility or toxicity more accurately at finer levels of resolution.

In spite of limitations, the database approach for working with large information sets is useful. At its current rate of expansion, scientific information is difficult to integrate and use creatively. Identifying trends and characteristics of this information base is a powerful use of database technology. It can provide new perspectives and help pose appropriate questions. While this database is a useful tool for literature review, its greatest utility may involve information processing for IPM or regulatory risk assessment.

Trends and research questions

Natural enemy and host/prey representation

Taxonomically, the natural enemy/pesticide literature focuses mostly on important biological control agents that attack pests on high-value crops (Theiling, 1987). Predators, and to a lesser extent, parasitoids of cotton, cereal grains, apple, citrus and greenhouse pests were most extensively represented. These high-value crops have large funding bases for research beyond that provided by industrial sources. Most selectivity research done on natural enemies depends on funds provided for more basic research. Published research on natural enemy/pesticide interactions is weighted toward systems where pest resistance and pest outbreaks have most commonly occurred (Croft and Brown, 1975). Undoubtly, ease of culturing, handling and testing natural enemies also influences the amount of research conducted for many natural enemy species.

While natural enemies are featured in this body of pesticide-impact literature, host or prey susceptibility status is critical to determine the selectivity of any given pesticide. Achieving selectivity is a general goal of natural enemy/pesticide research (Bartlett, 1964). Most hosts or prey listed in our database are indirect or pesticide-induced pests such as mites, aphids, scales and whiteflies. Because many direct, key pests are not sufficiently regulated by natural enemies to remain below stringent economic thresholds (e.g. Hoyt and Tanigoshi, 1983), selectivity research on their predators and parasitoids is less intensively pursued compared with pests that show good biological control potential. However, pesticides which control key pest species are often evaluated for their effects on the predators and parasites of secondary pests that occur in a given crop or ecosystem.

The lack of comparative toxicity data for pests and natural enemies is an artifact of the pesticide development and evaluation process. Efficacy of established rates of new compounds is evaluated on pests long before natural enemy assessments are conducted. During natural enemy impact evaluations, the comparative effects of "normal field rates" on pests are assumed to be the same

as in earlier efficacy studies. Earlier evaluations of impact on natural enemies should be made soon after pest effectiveness is verified. Comparative testing will become common only as selectivity is given higher priority in the pesticide design and registration process.

Pesticide representation

Insecticides dominate the pesticide-impact literature. This is reasonable because arthropod natural enemies are closely-related non-target species associated with pest insects. Relatively few studies feature side-effects of fungicides or herbicides, although this is slowly changing (Fig. 2). Even non-pesticidal agricultural chemicals such as plant growth regulators (Hislop et al., 1978; Gruys, 1980; Cranham and Solomon, 1981) nutrient sprays (Hislop et al., 1978) and the inert components of formulations (Wilkinson et al., 1978; Haverty, 1982) can adversely affect natural enemies. Perhaps screening studies could be put in order of priority for selected groups of these materials. Although most insecticides are harmful to natural enemies, individual acaricides and herbicides vary. Some of these compounds adversely effect predators and parasitoids, while others have a consistent pattern of harmlessness (Theiling, 1987).

Pesticide selectivity and toxicity

Selectivity ratios are valuable information for IPM. The ideal insecticide is applied at a rate which suppresses pest populations while allowing at least partial natural enemy survival. Unfortunately, very few selective pesticides with these features have been identified (Metcalf, 1980; Hull and Beers, 1985; Mullin and Croft, 1985). Even fewer physiologically-selective compounds have been used successfully in the field (Table 7). In our analysis, the most ideal selective compounds were those used against specific groups of pests such as mites or aphids.

Compounds demonstrating selectivity to many natural enemies over their hosts or prey on a particular crop are scarce (Croft and Whalon, 1982). Some of the newer insect growth regulators have a wider spectrum of selectivity, such as diflubenzuron (Anderson and Elliot, 1982; Zungoli et al., 1983; Broadbent and Pree, 1984), however their use is still limited with many crops (Crop Protection Chemicals Reference, 1986). At present, regulatory constraints and industry attitudes are not conducive to the development of broadly-selective pesticides. Pirimicarb, the most selective conventional insecticide identified in the present analysis (Table 7), is not currently registered in the U.S.A., partly because of economic factors influencing registration of the compound (Federal Register, 1981).

Trends in research for insecticide classes indicate some movement toward more selective products, especially for microbial insecticides and insect growth regulators (Fig. 3). However, actual use patterns of different pesticide groups are more disturbing (Pimentel, 1981). We conclude that overall toxicity to

natural enemies has actually increased from the inorganics to DDT and the organochlorines, and then to the organophosphates and carbamates, and finally to the synthetic pyrethroids (Fig. 9), which are slightly more toxic than the organophosphates and carbamates (Croft and Whalon, 1982). While the microbials and insect growth regulators offer selectivity, concern and scepticism surround registration, marketing and the eventual use of microbial pesticides and other selective products in mainstream agriculture (Senuta, 1987).

Susceptibility between natural enemy groups

Predatory natural enemies generally seem to be less susceptible to pesticides than are parasitoids, and natural enemies are usually more susceptible than their prey or hosts (Croft and Morse, 1979; Plapp, 1981; Mullin and Croft, 1985). Several hypotheses and some experimental evidence help to explain these differences. Differential detoxification, resistance and population dynamics among these groups of arthropods have been implicated (Croft and Morse, 1979; Mullin and Croft, 1984, 1985; Rosenheim and Hoy, 1986).

In our database analyses, numerical differences in average toxicity ratings of predators versus parasitoids for all pesticides or by pesticide class (Table 2) were small; however, the size of data sets, variability in test conditions, and diversity of species represented by computations in Table 2 were considerable. Even in these comparisons, predators were consistently less susceptible to all pesticides than were parasitoids.

More specific comparisons of toxicity ratings supported the hypothesis that predators are less susceptible to pesticides than parasitoids (Figs. 7, 8; Tables 3–5; Theiling, 1987). Scatterplots of predator or parasitoid families (see Figs. 7, 8) illustrated lower susceptibility as well as higher variability of response among predators. When toxicity means were calculated by natural enemy type for more precise, controlled laboratory assays (i.e. LD_{50} and LC_{50} data), differences were more pronounced. Predators (1890 records) averaged 3.53 and parasitoids (648 records), 3.78. These assays reflect innate susceptibility levels.

Predator–prey selectivity ratios were generally lower than parasitoid–host ratios. The average selectivity ratio for predators was 17.5, while the corresponding mean value for parasitoids was 83.4. Hence, predators are less susceptible relative to their prey than parasitoids relative to their hosts by a factor of 5. More specific selectivity ratio and sr:index calculations for predators and parasitoids confirm this trend (Tables 6, 7; Theiling, 1987).

Parasitoids may be committed to a more biologically complex life history than predators through co-evolution with their hosts (Huffaker, 1971). Perhaps parasitoids have lost the resiliency to adapt to their external environment as they have gained in host synchrony and specialization (Huffaker and Messenger, 1976). Thus, they may be less fit for survival as free-living organisms in a chemically-hostile environment. Relative to predators, parasitoids may have lower detoxification enzyme levels, sequestration potentials, higher pen-

etration levels or some combination of these and other toxicological factors (Croft and Mullin, 1984; Mullin and Croft, 1984, 1985).

On the other hand, greater evolutionary proximity to phytophagy may confer on predators an enhanced ability to detoxify or otherwise cope with xenobiotics, including pesticides (Mullin and Croft, 1985). Many predatory families contain both entomophagous and herbivorous species, e.g. Coccinellidae, Miridae, Pentatomidae, Lygaeidae, Cecidomyiidae. Most of these families contain pesticide-tolerant predatory species (Table 3). Parasitoidism and phytophagy rarely occur within the same family, and the presence of high levels of detoxification enzymes in parasitoids relative to their prey has been infrequently demonstrated (Mullin and Croft, 1985; Duffey et al., 1986).

Over time, predators appear to adapt better to pesticide pressure than parasitoids. Stable, high levels of pesticide resistance have not been documented among parasitoids, whereas they have been more commonly found among predators (Croft and Strickler, 1983). Arguments have been made in support of artificial selection of parasitoids with pesticides (Roush, 1979; Rosenheim and Hoy, 1986). While elevated LD_{50} values have been observed in field- and laboratory-selected parasitoid colonies to a limited extent (reviewed in Croft and Strickler, 1983), stable resistance levels comparable to predators have not been maintained.

This raises questions regarding the genetic plasticity of parasitoids (Huffaker, 1971; Graur, 1985; Rosenheim and Hoy, 1986). Limited pesticide resistance may be related to low genetic variability in response to toxins. Several hypotheses on comparative resistance development in natural enemies and pests have been proposed (Croft and Morse,1979; Tabashnik and Croft, 1985; Rosenheim and Hoy, 1986), but little information exists comparing predators and parasitoids.

In summary, while comparative research on natural enemy and herbivore responses to pesticides may be increasing, similar work comparing predators and parasitoids is largely forthcoming. Basic investigations of evolutionary and short-term responses of these organisms to natural chemicals and synthetic pesticides may explain their divergent responses.

Specificity of research

More detailed study of the effects of pesticides on arthropod natural enemies is evident, as suggested by analysis of the literature. Trends indicate that the scientific community has recognized the potential inaccuracy of extrapolating from pests to natural enemies to assess pesticide impact on biological control agents. Equivalent mortality from pesticides may have very different consequences for the two groups. For example, an equal reduction of both pest and natural enemy may be far more detrimental to the entomophage because its food supply needed for survival and reproduction has almost been eliminated.

On the other hand, the food supply of a crop-feeding pest is still abundant (Croft and Morse, 1979).

The study of sublethal pesticide effects on natural enemies is another example of increasing specificity of research. Mortality is the principal focus of pesticide impact studies on pests. However, minor disruptions can render a natural enemy ineffective for biological control (Brown, 1977). Documentation of the sublethal effects of pesticides on natural enemies is increasing. While most of the organosynthetic insecticides cause acute mortality to natural enemies at field rates, sublethal effects become important as residues diminish over time and re-entry into the habitat occurs. Furthermore, side-effects of the microbial pesticides and insect growth regulators are more commonly sublethal and chronic (Beckage, 1985; Flexner et al., 1986). Increased study of these types of pesticides and their differential impact on pests and their predators and parasites is critical to increase the use of selective pesticides in improved pest-control systems.

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